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DUAL-IMAGING OPTICAL SYSTEM

Field of the Invention

This invention pertains primarily to optical systems used in reduction-type projection-exposure apparatus such as projection steppers and scanners used in the manufacture of semiconductors. The invention is especially directed to such apparatus that employ catadioptric optical systems in their optical systems with resolution in the sub-micron levels of the ultraviolet wavelengths.

Background of the Invention

As circuit patterns for semiconductors become finer, higher levels of resolution are demanded of steppers and scanners that expose these patterns. To satisfy demands for higher resolution, the wavelength of the radiation employed must be reduced, and the numerical aperture (NA) of the optical system must be increased.

Only a few optical materials are adequately transmissive at shorter wavelengths. For wavelengths of 300 nm or less, the only currently available materials that can be used effectively are synthetic fused silica and fluorite.

The Abbe numbers of fused silica and fluorite are not sufficiently different from each other to allow complete correction of chromatic aberration. For this reason, at wavelengths of 300 nm or below, it is extremely

difficult to correct chromatic aberration in projection-optical systems comprised solely of standard refractive optical systems.

Fluorite itself suffers from certain disadvantages. The refractive index of fluorite changes relatively rapidly with variations in temperature, and fluorite polishes poorly. Thus, many optical systems do not use fluorite, resulting in systems with lenses of fused silica only. Such all-silica systems exhibit uncorrectable chromatic aberration.

Purely reflective optical systems avoid chromatic aberration, but such systems tend to be excessively large, and to require one or more aspheric reflecting surfaces. The production of (large) precision aspheric surfaces is extremely difficult.

As a result, various technologies making use of "catadioptric" optical systems (i.e., optical systems in which refractive elements are combined with reflective elements) have been proposed for reduction projection-optical systems. Among these have been several that propose the formation of an intermediate image one or more times within the optical system.

Previously proposed reduction projection-optical systems which form only one intermediate image are disclosed in Japanese laid-open patent documents 5-25170 (1993), 63-163319 (1988), 4-234722 (1992), and in U.S. Patent No. 4,779,966. Among these proposed systems, only those disclosed in Japanese laid-open patent document

4-234722 and U.S. Patent No. 4,779,966 use just one concave mirror.

Japanese laid-open patent document 4-234722 and U.S. Patent No. 4,779,966 disclose catadioptric optical projection systems comprising a concave mirror and a double-pass lens group. Incident light propagates through the double-pass lens group in a first direction, strikes the concave mirror, and then propagates, as reflected light, back through the double-pass lens group in a second direction opposite to the first direction. Because the double-pass lens groups of Japanese laid-open patent document 4-234722 and U.S. Patent No. 4,779,966 use only concave lenses and thus have negative power, the light entering the concave mirror is dispersed, requiring a relatively large-diameter concave mirror.

The double-pass lens group of Japanese laid-open patent document 4-234722 (1992) is completely symmetric, which reduces aberrations to an extreme degree, significantly reducing the aberration correction burden for the downstream refractive optical system. However, the completely symmetric configuration also reduces the distance between the intermediate image and the nearest optical element to such a degree that use of a beam-splitter is necessitated to effectively redirect the reflected light while allowing passage of the incident light.

The optical system disclosed in U.S. Patent No. 4,779,966 comprises a concave mirror in a second imaging

system that images an intermediate image onto the wafer. To provide adequate image brightness in this configuration, divergent light enters the concave mirror, requiring a relatively large-diameter mirror.

In optical systems utilizing several mirrors, it is possible to reduce the number of refractive lenses, but other problems arise.

In order to obtain adequate depth of focus with improved resolution, phase-shift reticles are often used. To most effectively use a phase-shift reticle, the ratio σ between the illuminating optical system NA and the imaging optical system NA should be variable. An aperture stop can be installed in the imaging system to provide or increase this variability. But, in a catadioptric imaging system, as, for example, in U.S. Patent No. 4,779,966, there is often no location for an effective aperture stop.

In catadioptric optical systems in which a double-pass lens system is employed in a demagnifying portion of the optical system, the demagnification reduces the allowable distance between the reflecting element and the wafer, so that few lenses can be placed in the optical path between the reflective element and the wafer. This necessarily limits the numerical aperture (NA), and thus the maximum brightness, of the optical system. Even if it were possible to realize an optical system with a high NA, many optical elements would have to be placed along a limited optical path length, so that the distance between

the wafer and the tip surface of the object lens (i.e., the working distance WD) would be undesirably short.

In conventional catadioptric optical systems, the optical path must be eccentric over at least a portion of its length. The adjustment procedure for the eccentric sections of such optical systems is difficult and makes the realization of precision systems essentially impossible.

The applicant has previously proposed a dual-imaging optical system which is designed with a first imaging system comprising a two-way optical system having a concave mirror and a double-pass lens group that allows light both incident to, and reflected from, the concave mirror to pass through the lens group. An intermediate image is formed by the first imaging system and an image of the intermediate image is formed by a second imaging system. A reflecting surface is provided to direct the light flux from the first imaging system toward the second imaging system.

This dual-imaging optical system allows a smaller diameter concave mirror, and provides an effective aperture-stop placement position, allowing a variable ratio σ based on the illuminating optical system NA and the imaging system NA for use with phase-shift reticles for resolution enhancement. It also allows for sufficient optical system brightness and an optical system where the working distance WD, the distance between the wafer and the nearest surface of the object imaging system, can be relatively long. It also makes the adjustment of the

eccentric section of the optical system easy, enabling the practical realization of a precision optical system.

While this dual-imaging optical system has many superior features, attempts to reduce the size of the optical system while maintaining image-forming performance results in increased distortion. That is, the optical system is not symmetric, so even if other aberrations are corrected, distortion will remain.

Also, when trying to correct distortion, astigmatism correction may be affected, and it is well known that it is extremely difficult to correct both types of aberration at the same time.

It is desirable to leave other types of well-corrected aberration as-is, and correct only the distortion or astigmatism aberration, especially the higher-order distortion.

In the manufacturing of high-precision optical systems, variance from product to product inevitably arises due to manufacturing tolerances. This variance results in different aberration levels for each optical system produced. Such manufacturing-error-induced aberrations are normally corrected by adjusting sections of the optical system. However, when there is asymmetric aberration of differing amounts across the image surface due to manufacturing tolerances, or when the generated aberration amounts are too great, it is often impossible to fully correct the system for manufacturing tolerances solely by adjusting sections of the optical system. In this case,

corrections can sometimes be made by inserting an aspheric, aberration-correcting plate near the final focused image. While such a correcting plate is effective in correcting "angle-of-view" aberrations (such as distortion and/or astigmatism) when placed as close as possible to the image surface, in practice, the presence of other adjusting devices or measuring equipment near the image surface normally requires that such plates be placed a sufficient distance away from the image surface such that other types of aberration (related to aperture) are also affected. This complicates the correction process.

Summary of the Invention

This invention provides a dual-imaging optical system that can effectively correct distortion to a high degree while providing a compact optical system, maintaining imaging performance, and correcting for manufacturing tolerances.

The invention comprises a dual-imaging optical system including a first imaging system that forms an intermediate image, and a second imaging system that forms an image of the intermediate image.

A reflecting surface directs light flux from the first imaging system to the second imaging system in this dual-imaging optical system.

A correcting optical system for correcting distortion, astigmatism, and/or accumulated manufacturing tolerances is placed at or near the intermediate image.

The correcting optical system includes at least one aspheric surface. The aspheric optical surface may be a lens surface of a lens near the reflecting surface, or the reflecting surface itself may be made aspheric.

The shape of the aspheric optical surface can be axially symmetric. Alternatively, the aspheric optical surface can be a circular or non-circular cylindrical surface. Further alternatively, the surface can be completely asymmetric. Using the symmetric configuration, at least distortion, spherical aberration of the pupil, and accumulated manufacturing tolerances of the optical system can be corrected.

In order to correct distortion or astigmatism, correct accumulated manufacturing tolerances, and not create other types of distortion, a correcting optical system in the form of at least one aspheric optical surface is placed near the intermediate image. The placement of an aspheric correcting optical system near the intermediate image is especially effective for correcting higher-order distortion or astigmatism. A lens with an aspheric surface may be used for this purpose. On the other hand, since the reflecting surface is near the intermediate image, the reflecting surface itself may be made aspheric and used as the correcting optical system. The reflecting surface can be placed very close to or even at the intermediate image, so that making the reflecting-surface aspheric allows designating the desired distortion or astigmatic aberration

correction in a straightforward manner, with little effect on other types of aberration.

The aspheric surface is preferably axially symmetric. Alternatively, an aspheric lens surface could be combined with a rectangular reflecting surface shaped so that change occurred only longitudinally in the reflecting surface. For the same sort of effect, the aspheric lens surface can be a circular or non-circular cylindrical (toric) surface. In other words, the effect that the shape of the aspheric surface has on distortion would be primarily dependent upon changes in the longitudinal inclination of the aspheric surface, and changes in the inclination in the shorter direction would not change the image height significantly, so it would not have that great an effect on distortion. A completely asymmetric aspheric surface may also be used as a lens surface or a reflecting surface.

From the point of view of machining the aspheric surface, simplicity is preferred, such that an axially symmetric surface or one which can change in a longitudinal direction only (a circular or non-circular cylindrical surface) would be better.

An axially asymmetric aspheric surface may be produced by performing aspheric surface machining symmetrically around the optical axis. A circular or non-circular cylindrical surface may be reproduced with a single-direction aspheric surface machining device.

When there are different levels of aberration across the image surface due to manufacturing error, a completely asymmetric aberration-correction surface can be used, depending upon the amount of aberration. Naturally, it would be placed close to the intermediate image, so that just the corrections pertaining to the angle of view could be prioritized as necessary.

The above-summarized invention allows near-perfect correction of the particular aberrations which increase with reductions in the size of the optical system, and even near-perfect correction of hard-to-correct higher-order aberration and distortion and aberration due to manufacturing, while avoiding almost all effects on other aberrations, such as spherical aberration, coma aberration, sine conditions, and axial chromatic aberration.

The foregoing and other objects, features, and advantages of the invention will become more apparent from the following detailed description of example embodiments which proceeds with reference to the accompanying drawings.

Brief Description of Drawings

FIGS. 1(a)-1(c) are a schematic diagram of a first representative embodiment of the catadioptric reduction optical system of the present invention. FIGS. 1(a) and 1(b) are plan views, respectively, of the reticle and wafer of FIG. 1(c).

FIGS. 2(a)-2(c) are a schematic diagram of a second representative embodiment of the catadioptric

reduction optical system of the present invention.

FIGS. 2(a) and 2(b) are plan views, respectively, of the reticle and wafer of FIG. 2(c).

FIG. 3 is an optical diagram of the catadioptric reduction optical system of Example Embodiment 1, employing in imaging system B a lens element L having an aspheric surface.

FIG. 4 is an expanded optical path diagram of Example Embodiment 1.

FIGS. 5(a), 5(b), 5(c), 5(d), and 5(e) are, respectively, graphical representations of spherical aberration, astigmatic aberration, distortion, coma, and (chromatic) magnification aberration exhibited by Example Embodiment 1.

FIG. 6 is an optical diagram of the catadioptric reduction optical system of Example Embodiment 2, in which the reflecting surface M_2 is aspheric.

FIG. 7 is a graphical representation of the transverse aberration exhibited by Example Embodiment 2.

FIG. 8 is a graphical representation of the distortion exhibited by Example Embodiment 2.

Detailed Description

FIGS. 1(a)-1(c) show a first representative embodiment of the invention employed in a projection-optical system wherein a circuit pattern on a reticle R is reduced and transferred onto a semiconductor wafer W. This projection-optical system has a first imaging system A that

forms an intermediate image of the pattern defined by the reticle R, a reflecting surface M_2 placed close to the intermediate image, and a second imaging system B that forms an image of the intermediate image on the wafer W.

In the Example Embodiments described below, as seen in FIGS. 3, 4, and 6, the first imaging system A preferably comprises four refractive lenses and one concave mirror M_1. Light from the reticle R passes through the first imaging system A in both directions. The reflecting surface M_2 is placed to direct the light returning from the first imaging system A into the second imaging system B. This reflecting surface M_2 may be aspheric.

In the Example Embodiments described below, the second imaging system B preferably comprises 17 refractive lenses. An aperture stop S is placed inside the second imaging system B. Of the lens surfaces in the second imaging system B, the surface closest to the reflecting surface M_2 may be aspheric as an alternative to, or in addition to, the reflecting surface M_2 being aspheric.

By way of example, the projection-optical system of FIGS. 1(a)-1(c) is a lens system with a magnification ratio of 1/4x, an image-side numerical aperture NA of 0.6, a maximum object height of 72 mm, and a rectangular aperture a. The rectangular aperture corresponds to a rectangular illumination field, with a vertical length of 16 to 40 mm, preferably 24 mm, and a horizontal length of 120 mm. The refractive lenses can be made of fused silica (SiO_2) or calcium fluoride (CaF_2). At the 193-nm

wavelength from an ultraviolet excimer laser, the chromatic axial and magnification aberration is corrected for wavelength widths of ±0.1 nm.

FIGS. 2(a)-2(c) show a schematic diagram of a second representative embodiment, in which a reflecting surface M_3 is placed inside the second imaging system B, and the direction of travel of the light illuminating the reticle R is aligned with the direction of travel of the light exposing the wafer W. Other aspects of this embodiment are the same as for the first embodiment, and as such, it has the same imaging performance as the first embodiment.

Example Embodiment 1

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~~FIG. 3 shows an optical path diagram of Example Embodiment 1 of a catadioptric optical system according to the present invention. The optical system of FIG. 3 can be used with the embodiment of FIGS. 1(a)-1(c) or 2(a)-2(c). In FIG. 3, the reflecting surface M_2 is planar and the surface of lens element L in the optical system B nearest to the reflecting surface M_2 is aspheric.~~

FIG. 4 shows an expanded optical path diagram of Example Embodiment 1. That is, in order to avoid the complications of reflected light in the drawings, the light rays are shown in Fig. 4 as always propagating in the same direction.

Table 1 below lists the surface data of Example Embodiment 1. The optical path of FIG. 4 is taken in Table

1, with the reflecting surface M_3 omitted, and with a flat reflecting surface inserted, as surface 10, to represent the unfolding of the optical path as shown in FIG. 4. In Table 1, the first column lists the surface number from the reticle R, the second column, labeled "r," lists the radius of curvature for each of the surfaces, the third column, labeled "d," lists the axial distance from each surface to the adjacent surface, the fourth column lists the material for each lens, and the fifth column lists the group designation for each optical element. The lens surface featuring an asterisk (*) in the first column is aspheric. An asterisk in column 5 indicates a return path.

The shape of the aspheric surface in Example Embodiment 1 is represented by the following equation,

$$S(y) = \frac{\frac{y^2}{r}}{1+\sqrt{1-\frac{\kappa y^2}{r^2}}} + \sum_{i=2}^{N} C_{2i} y^{2i}$$

wherein y is the height perpendicular to the optical axis, S(y) is the amount of sag parallel to the optical axis at height y, r is the radius of curvature on the optical axis, κ is the conic coefficient, and C_n is the nth aspheric surface coefficient. The conic coefficient κ and the aspheric surface coefficients for Example Embodiment 1 are shown in Table 2 (entitled Example Embodiment 1 Aspheric Surface Data), below.

The refractive index n and the Abbe number ν ±0.1 nm of the standard wavelength in relation to the standard wavelength used for fused silica (SiO_2) and calcium fluoride (CaF_2) are as follows.

SiO_2: n = 1.56019 ν = 1780
CaF_2: n = 1.50138 ν = 2550

FIGS. 5(a), 5(b), 5(c), 5(d), and 5(e) depict representative plots of spherical aberration, astigmatic aberration, distortion, coma, and magnification aberration, respectively, exhibited by Example Embodiment 1. In FIG. 5(a), SC represents deviation from the sine condition. Also, in each of FIGS. 5(a)-5(d), Y is the image height, P is the standard wavelength +0.1 nm, J is the standard wavelength and Q is the standard wavelength -0.1 nm. As is clear from each of FIGS. 5(a)-5(e), spherical aberration, coma, astigmatism, and distortion are all corrected to a very high degree, demonstrating the superior performance of this optical system.

Note that, in this example embodiment, a lens having an aspheric surface was placed immediately after the reflecting surface M_2. Alternatively, an aspheric lens surface can be placed immediately in front of the reflecting surface M_2. In Table 1, surfaces 1 and 10 are virtual reflecting surfaces.

Table 1

Example Embodiment 1 Surface Data

No.	r	d	Material	Group
0	---	160.00000		reticle
1	∞	98.99633		
2	1140.26480	40.00000	CaF_2	A
3	-579.11541	255.01123		
4	1182.85550	15.00000	SiO_2	A
5	409.99148	124.15981		
6	1269.25390	30.00000	SiO_2	A
7	-1392.04400	366.83229		
8	-269.86608	15.00000	SiO_2	A
9	-2727.50700	70.00000		
10	∞	0		
11	443.32063	70.00000		A (M_1) (Concave Mirror)
12	2727.50730	15.00000	SiO_2	A*
13	269.86608	366.83229		
14	1392.04380	30.00000	SiO_2	A*
15	-1269.25400	124.15981		
16	-409.99148	15.00000	SiO_2	A*
17	-1182.85600	255.01123		
18	579.11541	40.00000	CaF_2	A*
19	-1140.26500	98.99633		
20	∞	73.73678		M_2 (Reflecting Surface)

*21	-1617.55100	30.00000	SiO_2	B
22	-946.74609	0.10000		
23	443.20483	30.00000	CaF_2	B
24	-613.15563	5.00000		
25	-1133.72600	24.00000	SiO_2	B
26	624.49548	10.94895		
27	-718.16831	24.00000	SiO_2	B
28	413.72496	14.47012		
29	568.99448	30.00000	CaF_2	B
30	-356.83594	2.54622		
31	-303.66460	35.00000	SiO_2	B
32	-748.52031	0.10000		
33	1067.17910	35.00000	CaF_2	B
34	-916.15492	732.19624		
35	639.63609	40.00000	SiO_2	B
36	-1837.83000	1.00000		
37	---	32.10226		B (Aperture Stop)
38	851.14867	30.00000	SiO_2	B
39	596.88123	1.26000		
40	256.43786	50.00000	CaF_2	B
41	4113.75620	18.94853		
42	-477.89543	88.37165	SiO_2	B
43	-606.10781	0.51272		
44	690.95035	32.52509	CaF_2	B
45	-3442.72000	0.36748		

46	153.43477	69.82314	SiO_2	B
47	132.23252	14.68969		
48	145.32257	45.19542	SiO_2	B
49	1541.26430	4.20000		
50	-1123.78400	22.68000	SiO_2	B
51	1762.68930	1.91993		
52	685.77175	31.14230	SiO_2	B
53	958.60472	2.25212		
54	399.11389	31.27391	SiO_2	B
55	5403.63050	15.00000		Wafer

Table 2

Example Embodiment 1 Aspheric Surface Data

Lens Surface Number: 21 $\kappa = 1.0000$

$C_4 = -2.38900 \times 10^{-9}$ $C_6 = -4.71130 \times 10^{-15}$

$C_8 = -2.05220 \times 10^{-19}$ $C_{10} = 8.36490 \times 10^{-24}$

Example Embodiment 2

FIG. 6 shows an optical path diagram of Example Embodiment 2 of a catadioptric optical system according to the present invention. The optical system of FIG. 6 can be used with the embodiment of FIGS. 1(a)-1(c) or 2(a)-2(c). In FIG. 6, the reflecting surface M_2 is aspheric and the optical surface of lens L in the optical system B nearest to the reflecting surface M_2 is spherical.

Table 3 below lists the surface data of Example Embodiment 2. An optical path corresponding to FIG. 1 is taken in Table 3, so that mirror M_3 is omitted. As in Table 1, in Table 3, the first column lists the surface number from the reticle R, the second column, labeled "r," lists the radius of curvature for each of the surfaces, the third column, labeled "d," lists the axial distance from each surface to the next surface, the fourth column lists the material for each lens, and the fifth column lists the group designation for each optical element. The surface featuring an asterisk (*) in the first column is aspheric. An asterisk in column 5 indicates a return path. In contrast with Table 1, negative distances are employed in Table 3 to represent the return path of reflected light, rather than negative radii of curvature. In Table 3, surfaces 1-6, 13, and 26-31 are virtual surfaces that were considered as part of the lens-design process.

The shape of the aspheric surface of Example Embodiment 2 may be represented by the equation presented above relative to Example Embodiment 1. The conic coefficient κ and the aspheric surface coefficients for Example Embodiment 2 are shown in Table 4, (entitled Example Embodiment 2 Aspheric Surface Data), below.

FIG. 7 depicts representative plots of coma exhibited by Example Embodiment 2. In each of the diagrams, Y is the image height. As is clear from these aberration diagrams, the optical system of Example Embodiment 2 provides excellent performance, particularly

in that coma is corrected nearly to the point of no aberration. FIG. 8 provides plots of distortion exhibited by Example Embodiment 2. As is clear from the distortion curve, distortion correction is extremely good.

Table 3

Example Embodiment 2 Surface Data

No.	r	d	Material	Group
0	---	60.000000		reticle
1	∞	0		
2	∞	30.000000		
3	∞	0		
4	∞	80.000000		
5	∞	0		
6	∞	21.110201		
7	1363.11994	36.000000	CaF_2	A
8	-404.99434	279.630076		
9	1408.93350	13.500000	SiO_2	A
10	376.65770	116.466055		
11	906.81981	27.000000	SiO_2	A
12	-1332.26491	154.962803		
13	∞	175.635036		
14	-249.08892	13.500000	SiO_2	A
15	-3128.27181	63.000000		
16	-401.41197	-63.000000		A (M_1) (Concave Mirror)
17	-3128.27181	-13.500000	SiO_2	A*

18	-249.08892	-175.635036		
19	∞	-154.962803		
20	-1332.26491	-27.000000	SiO_2	A*
21	906.81981	-116.466055		
22	376.65770	-13.500000	SiO_2	A*
23	1408.93350	-279.630076		
24	-404.99434	-36.000000	CaF_2	A*
*25	1363.11994	-21.110201		M_2 (Reflecting Surface)
26	∞	0		
27	∞	0		
28	∞	0		
29	∞	0		
30	∞	0		
31	∞	130. 000000		
32	2229.03311	24.000000	SiO_2	B
33	408.22661	3.000000		
34	569.14187	27.000000	CaF_2	B
35	-444.32289	4.500000		
36	1784.92158	21.600000	SiO_2	B
37	-2577.16606	10.722977		
38	-343.44849	21.600000	SiO_2	B
39	1202.96387	12.859591		
40	1625.87851	47.000000	CaF_2	B
41	-195.20517	2.412834		
42	-193.18029	31.500000	SiO_2	B
43	-1287.21632	0.100000		

44	730.56017	31.500000	CaF_2	B
45	-2127.69381	556.238917		
46	2508.51186	36.000000	SiO_2	B
47	-1178.02445	162.012540		
48	---	39.867585	(Aperture Stop)	
49	303.62383	27.000000	SiO_2	B
50	440.67155	1.134000		
51	249.11054	45.000000	CaF_2	B
52	3674.25611	17.045914		
53	-543.69897	75.048590	SiO_2	B
54	-781.60219	0.461446		
55	611.86734	29.284957	CaF_2	B
56	-4354.55637	0.330733		
57	142.52792	62.831346	SiO_2	B
58	128.33358	13.206846		
59	142.57235	40.662754	SiO_2	B
60	754.18207	3.780000		
61	-1327.11593	20.412000	SiO_2	B
62	531.69413	1.727935		
63	375.03771	28.020164	SiO_2	B
64	779.50239	2.026905		
65	283.45101	25.490979	SiO_2	B
66	4863.26742	15.000000	Wafer	

Table 4

Example Embodiment 2 Aspheric Data

Surface Number: 25 $\kappa = 1.0000$

$C_4 = -0.162401 \times 10^{-10}$ $C_6 = -0.117682 \times 10^{-15}$

$C_8 = -0.123567 \times 10^{-19}$ $C_{10} = 0.274232 \times 10^{-25}$

Having illustrated and demonstrated the principles of the invention in example embodiments, it should be apparent to those skilled in the art that the preferred embodiments can be modified in arrangement and detail without departing from such principles. I claim as the invention all that comes within the scope of the following claims.